

## **An Investigation of Dynamical Processes Influencing Sediment Transport and Morphological Change in Skagit Bay using an Unstructured Grid Coastal Ocean Model**

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### **LONG-TERM GOALS**

The long term goal of this project was to build a high-resolution coupled hydrodynamic-sediment model to examine the relative importance of the principal mechanisms controlling the morphodynamics of Skagit Bay. Critical to the success was the availability of measurements from the extensive observation program supported through the tidal flats DRI which would allow us to examine the capability of a state of the art coastal ocean model, and determine what future extensions may be necessary for continued discovery in this field. Through extensive grid refinement efforts and available high-fidelity bathymetry, a better understanding of the mesh resolution required to resolve the critical processes was gained. This will guide future application of this class of model.

### **OBJECTIVES**

The primary objective of the project was to configure an advanced coupled hydrodynamic-sediment model for simulation of the circulation and sediment transport in Skagit Bay. The model was designed to resolve the range of required scales from the open boundary in Puget Sound (~ 50 km) to the channel networks on the flats (~10-100 m). The coupled model was validated using available measurements to determine the capabilities and needs of such a system for this class of application. Grid convergence studies were performed to determine the necessary mesh resolution required to resolve the dominant processes.

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## APPROACH

Due to the complexity of the coastline and bathymetry and the large range in dynamical scales in macrotidal estuaries, the unstructured-grid coastal ocean model FVCOM was selected. FVCOM is a Fortran90 software package for the simulation of ocean processes in coastal regions (Chen et al., 2003, 2006). The publicly available model has a growing user base and has been used for a wide variety of applications, including work in Skagit Bay (Yang and Khangaonkar, 2008). The kernel of the code computes a solution of the hydrostatic primitive equations on unstructured grids using a finite-volume flux formulation. For the vertical discretization, a generalized terrain-following coordinate is employed. The model is fully parallelized using a Single Program Multiple Data (SPMD) approach (Cowles, 2008). FVCOM will be coupled with the Community Sediment Transport Modeling System (<http://woodshole.er.usgs.gov/project-pages/sediment-transport/>). The model includes transport of both the suspended load and bedload. The number of sediment classes is flexible, and for each class, parameters such as critical shear stress, mean diameter, and settling velocity must be defined. Complex bed dynamics are included with a user-prescribed number of layers defined by the layer number, fractions of each sediment class, an age, and a thickness.

## WORK COMPLETED

### 1. Personnel

A graduate student (Yeonkil Jung) was supported by this project during FY09 and FY10.

### 2. Skagit Bay Model Development

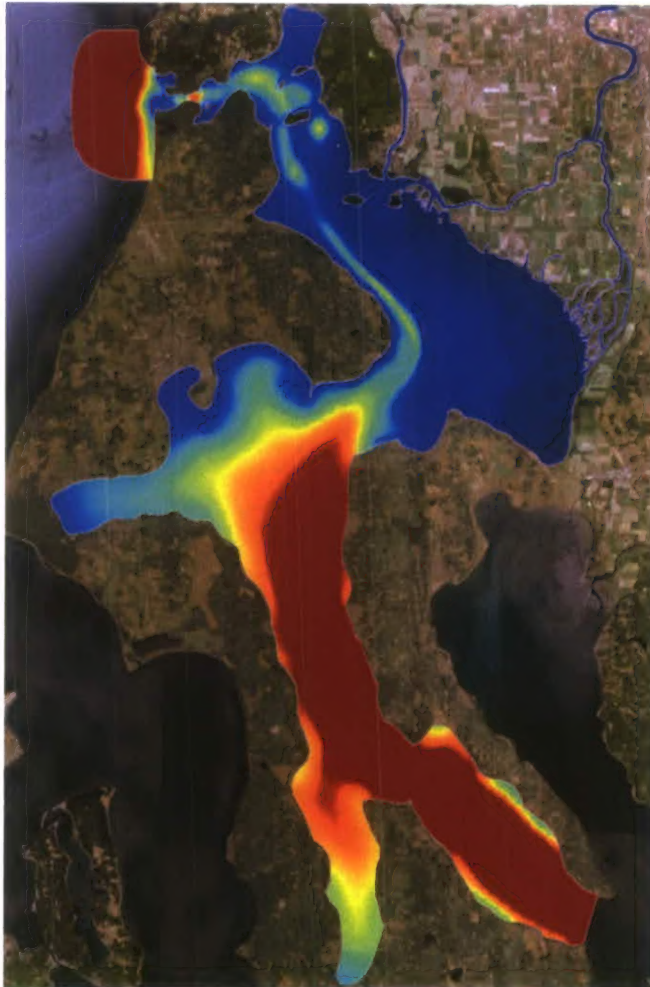
Following acquisition of the FVCOM Skagit Bay model from PNNL, the model was modified to make it suitable for examining the key scientific issues of the DRI. This included an increase in the resolution, modification of the domain, and improvement of the bathymetry. These are outlined in more detail below.

#### Domain

The model boundaries were extended into Juan de Fuca strait and through the Saratoga Passage to the south end of Whidbey Island at Sandy Point (Fig 1). The extensions were performed to ensure that the open boundary regions outside Skagit Bay contained had a large enough volume relative to the tidal prism to reduce the influence of the open boundary hydrography and sediment concentration on the interior model solution. The model is forced by tides at three open boundaries: Sandy Pt, Juan de Fuca, and Swinomish.

#### Bathymetry

The bathymetry consists primarily of two components, the Puget Sound Digital Elevation Map (PSDEM2005) with full coverage of the model domain and the SRSC Fir Island



**Figure 1: FVCOM Skagit Bay Domain and Bathymetry (Google Earth)**

River up to Mt. Vernon along with Steamboat and Freshwater Slough were provided to D. Ralston. De-tided depth collected from the WHOI survey (Geyer et al.) was then interpolated on the tracks and applied to model rivers under the assumption of zero cross-river bathymetric gradients. While this method produced reasonable slopes, some modification at the North/South fork split of the Skagit River were necessary to maintain continuity. Deepwater Slough was graded in the same manner, although at this time there is limited flux through the Slough. Bathymetry in the Swinomish was modified to enforce the (dredged) controlling depth of 6.8 feet.

#### Forcing and Bottom Roughness

The model is forced using freshwater flux from the Mt. Vernon stream gauge and specified sea surface elevation at the open boundaries. Tidal forcing at open boundary

Lidar survey, primarily constrained to the upper flats along Fir Island. This data was projected and reinterpolated into geographic coordinates by Rich Signell (USGS Woods Hole) and is available for download and interrogation through several mechanisms via the USGS Thredds catalog ([http://coast-enviro.er.usgs.gov/thredds/bathy\\_catalog.html](http://coast-enviro.er.usgs.gov/thredds/bathy_catalog.html), Puget Sound DEM: 2005).

On the South Fork flats, the bathymetry is still influenced by artifacts present in the DEM. Several attempts were made to eliminate these artifacts which manifest themselves as lines of discontinuity in the bathymetry in roughly the along-flat direction at intervals of roughly a kilometer. These were dealt with by smoothing in the cross-flat direction to try to maintain a reasonable large-scale cross-flat slope without aliasing critical channel features. Digital elevation in the primary river beds was estimated in collaboration with Dave Ralston (WHOI). Channel centerlines for the North Fork, South Fork, and Main Branch of the Skagit

into the Juan de Fuca Strait was adjusted to give better results for the tidal harmonics in the upper portion of the Bay. The high energy flows through Deception Pass are associated with intense form drag and lateral mixing at scales that the model is unable to resolve. The head loss through Deception Pass has been captured by changes in the lateral boundaries and bottom friction to achieve higher fidelity in the tidal harmonics from the open boundary to the interior of Skagit Bay. A spatially variable bottom roughness was applied to reflect the distribution of surficial sediments in Skagit Bay, Saratoga Passage, and Deception Pass.

#### Model Versions

Two series of models were generated. The 3.xx series models were generated using the mesh generation component of the Surface Modeling System (SMS) software which uses an advancing front technique to generate Delaunay-conforming grids. Working with D. Ralston (WHOI) these models have been continually refined to ensure stability in the integration while maintaining the level of necessary resolution. Two versions (3.15, 3.17) were used by D. Ralston for hindcast simulations of Skagit Bay. A summary of metrics for these models is included below. The 4.xx series of models are generated using the open source meshing software *gmsh* (<http://www.geuz.org/gmsh/>). This software has the capability of performing automated adaptive mesh refinement. The mesh can be adapted locally by specifying a background length scale to *gmsh*. Version 4.3, a relatively coarse mesh (table 1) has been used for calibrating and validating the tidal dynamics. Mesh model 4.3 has been employed by J. Lerczak (OSU) for an ONR supported study of annual and inter-annual variations in the hydrodynamics of the Skagit tidal flats.

Model	Elements	Layers	Resolution [Flats/Mean]	Time Step (s)	iterations/(core-hour)
skg3.15	188K	21	10m / 37m	0.5	150
skg3.17	112K	21	20m / 50m	1	255
skg4.3	15K	11	100m / 200m	5	7000 (barotropic)

**Table 1: Specifications of Current Skagit Models**

### **3. Code Development**

#### Sediment Model

Dynamics for cohesive sediment transport have been added to the sediment model in FVCOM. These have been extracted primarily from the implementation of the Community Sediment Transport Modelling System (CSTMS) currently available in the CSTMS branch of the Regional Ocean Model System (ROMS, <http://woodshole.er.usgs.gov/project-pages/sediment-transport/>). The principal modification to the existing FVCOM sediment model was the treatment of the bed. For cohesive substrates, the critical shear stress is a property of the bed which evolves due to consolidation, swelling, and bioturbation.

To test the updated FVCOM sediment model we have developed a wrapper to the module to drive 1-D solutions of sediment in the water column. Time-dependent physical fields (eddy diffusivity, bottom stress, and depth) are generated by the General Ocean Turbulence Model (GOTM) and are used to drive the model. This enables controlled testing of dynamics and sediment algorithms for problems that vary slowly in the horizontal. With C. Sherwood (USGS, Woods Hole) we developed a standardized set of 1-D test cases for the purpose of debugging as well as testing the CSTMS model dynamics in FVCOM.

The flux discretization of the bedload transport in the FVCOM implementation of the Community Sediment Transport Modeling System was modified to improve stability by employing an upwind formulation. The discretization of the vertical advection of the sediment concentration was adjusted to add alternative forms of the flux limiter.

#### Postprocessing

In the interest of providing ease of access to model results for other investigators, a postprocessing program was developed to convert output from FVCOM to files compatible with the General NOAA Operational Modeling Environment (GNOME: <http://response.restoration.noaa.gov/index.php>). This effort was initiated by R. Signell (USGS, WHOI) who also organized interaction with GNOME developers. This program is included as a utility in current releases of FVCOM.

#### **4. Mesh Refinement Study**

An open-loop h-refinement method was integrated into the FVCOM model. The open source mesh generator *GMSH* was used to automate mesh generation for the Skagit domain as well as several idealized tidal flats. One refinement loop consists of: 1.) integration of the flowfield over 20 tidal cycles on two mesh levels, (fine, coarse); 2.) construction of a background mesh lengthscale distribution using error estimates ; 3.) Regeneration of a new pair of fine and coarse meshes using the lengthscale distribution. Error estimates were derived from Richardson's extrapolation as well as direction estimates of numerical diffusion using the method of Burchard and Rennau (2008). The basic method was also used to generate a sequence of related meshes of increasing resolution to evaluate the grid dependence of the flow solution in Skagit Bay using observed velocities and tidal harmonics.

#### **5. Wet/Dry Resolving Shallow Water Equation Solver**

Associated with the propagation of the wet/dry front across the tidal flats and sheet flow during drainage are large shear stresses which make important contributions to the sediment fluxes during the tidal cycle. In FVCOM, the wet/dry scheme employs a fencing technique whereas the model cells are switched from a wet state to a dry state if the local depth falls below a minimum threshold (typically 5-10cm). It is not clear what

the impacts of fencing method and associated parameters are on the ability of FVCOM to resolve the time varying bed stress during the flooding/drying process. In order to evaluate this, a shallow water equation (SWE) solver has been developed which can resolve the wet/dry front exactly. The SWE solver uses an approximate Riemann approach based on wave fluctuations (Leveque, 1997). The source term is included as a point source at the cell interface (George, 2008) and the scheme utilizes Einfeldt speeds to maintain depth positivity. A flux corrector is used to maintain second order accuracy in space. The integrator is embedded in the Structured Adaptive Mesh Refinement Application Infrastructure (SAMRAI, <https://computation.llnl.gov/casc/SAMRAI/>) which provides the domain decomposition-based parallelization and Cartesian adaptive mesh refinement. The SWE solver is used for comparative studies with FVCOM of the detailed flooding/drying process and associated shear stresses.

## RESULTS

### 1. Tidal Modeling

Considering the depth of water and the relative protection and short fetch of the Bay, the tides represent the dominant external forcing over the broad scale of the flats and thus must be simulated as accurately as possible. However due to the extensive flooding and drying of the flats, the lateral mixing associated with the extreme currents of Deception Pass and the diurnal inequality, achieving high level of tidal model skill is challenging. A coarse model has been used for testing the model's ability to reproduce the tidal harmonics at stations around the Bay. This model runs quickly (Table 1) and thus is useful for tidal calibration. This model can be used to inform the forcing and setup of the high-resolution models which are too large to be practical for anything but production runs. Two key with the tidal forcing are the selection of open boundary forcing at the Juan de Fuca open boundary where there are no available harmonics and the treatment of Deception Pass. Tidal harmonics are compared at 9 stations in the domain: Deception Pass Park, Holly Farms Harbor, GreenBank, Coupeville, Crescent Harbor, Sneecoosh Point, Ala Spit, Corney Bay, and Yokeko Point. For the  $M_2$  amplitude and phase (dominant constituent) the average amplitude error is 3.3 cm and the average phase error is  $4.5^\circ$ . The primary source of model-observation error is the upper Skagit where the model leads the observations in the  $M_2$  constituent by approximately  $6^\circ$ . Work is continuing on parameterization of the bottom friction in Deception Pass to improve the tidal response in the upper Skagit. Spatially distribution of model-computed  $M_2$  amplitude (m) and phase ( $^\circ$ G) are shown in Figure 2.

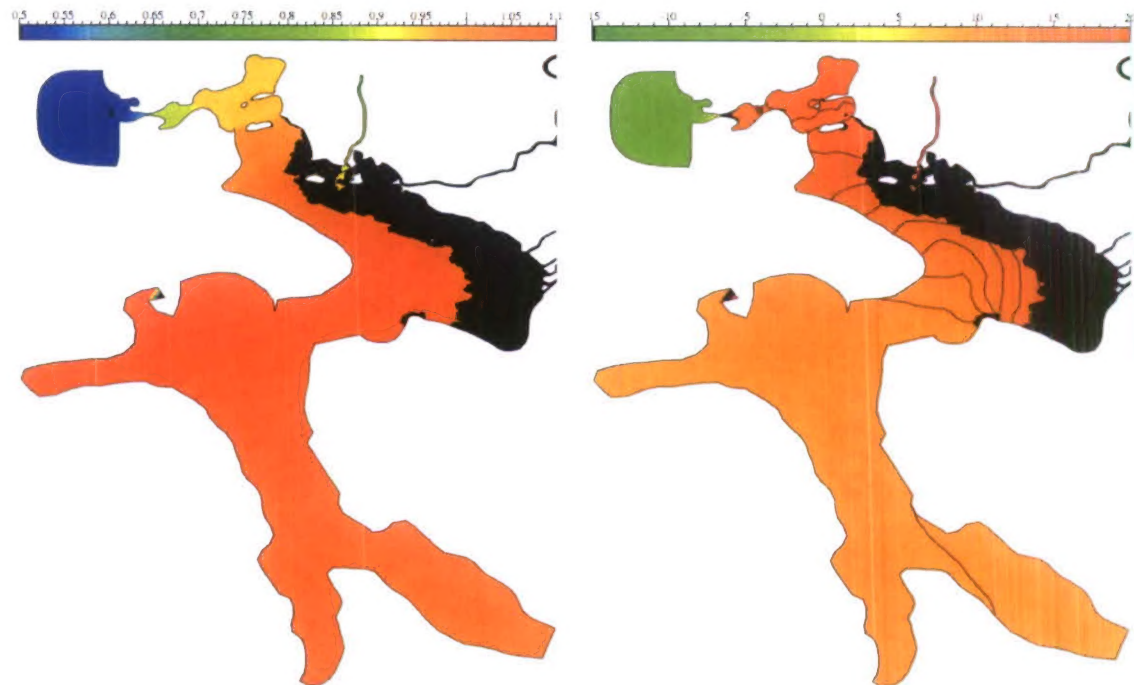


Figure 2: Model-Computed M2 Amplitude (m) [left] and phase ( $^{\circ}$ G) [right] in water greater than 2-m depth.

## 2. FVCOM-CSTMS testing

With guidance from C. Sherwood (USGS), a suite of 1-D test cases for the FVCOM-CSTMS model were developed (Table 1). These cases were used to debug and to test the sediment dynamics module of FVCOM using a range of forcing scenarios. The test cases allow evaluation of parameter sensitivity and comparison with ROMS-CSTMS (Figure 3).

Test Case	Open Channel	Tidal Forcing	Event Forcing	Settling Chamber
Source	Warner et al, 2008	Sherwood et al, 2008 ppt	Sherwood et al, 2008 ppt.	Sherwood et al., 2008 ppt.
Tests	Steady-state equilibrium, turbulence models	Time-varying erosion/deposition, bed composition	Dynamics across two events including bed dynamics	Quiescent settling, steady state bed composition
Physical Forcing	Constant Pressure Gradient	Harmonic Pressure Gradient	Time-varying Surface Stress	None
Sed Classes	Sand	Mud/Mud	Mud/Mud	Mud/Mud

Table 1: FVCOM-CSTMS 1-D Test Cases

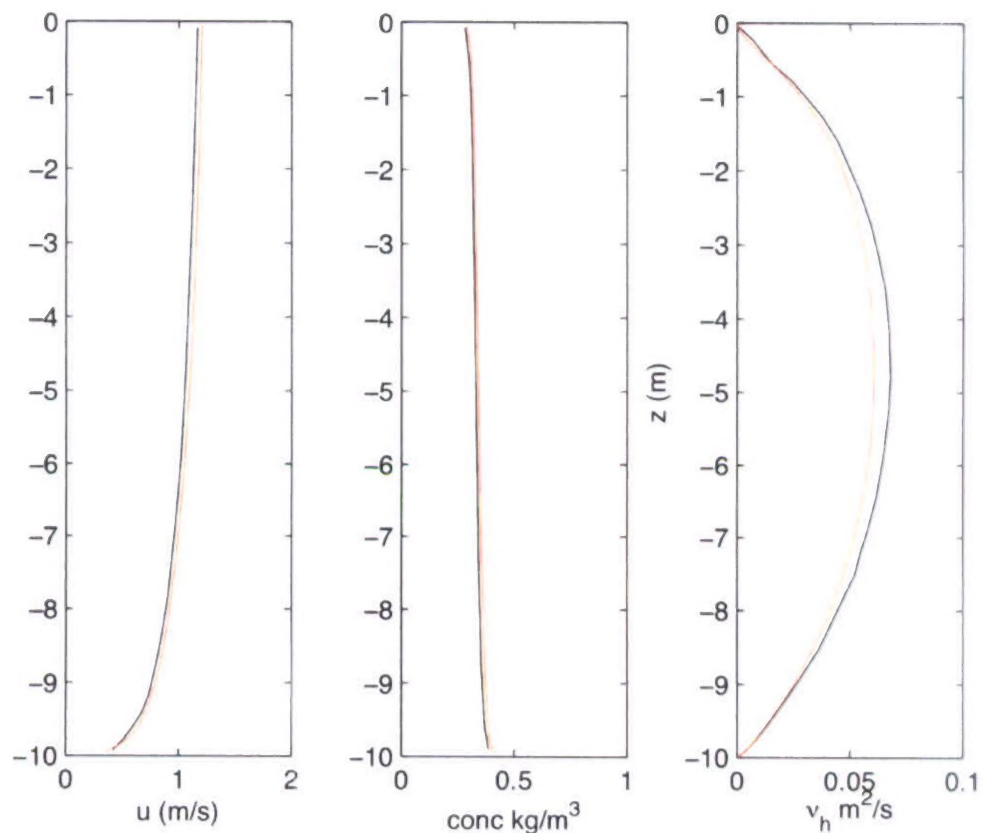
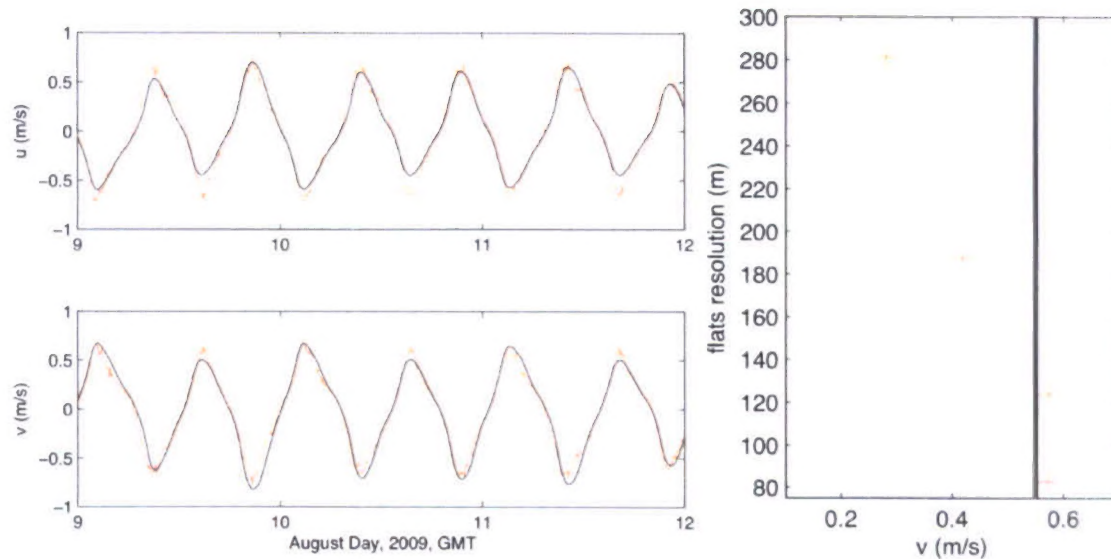


Figure 3: Comparison of FVCOM-CSTMS (red) and ROMS-CSTMS (black) for the open channel sediment test case.

### 3. Grid Refinement Studies

A sequence of meshes were constructed with the automatic mesh generator GMSH to evaluate the grid convergence of the Skagit model using tidal harmonics and ADCP data collected by Friday Harbor Laboratories in the main channel near Goat Island. The model reproduces well the phase and amplitude variation over the domain as well as the sawtooth characteristic of the velocities at the ADCP site (Figure 4). The grid refinement study indicated that grid resolved solutions of the large scale barotropic field can be obtained using a model with a mesh lengthscale of 100m on the Skagit flats (Figure 4).



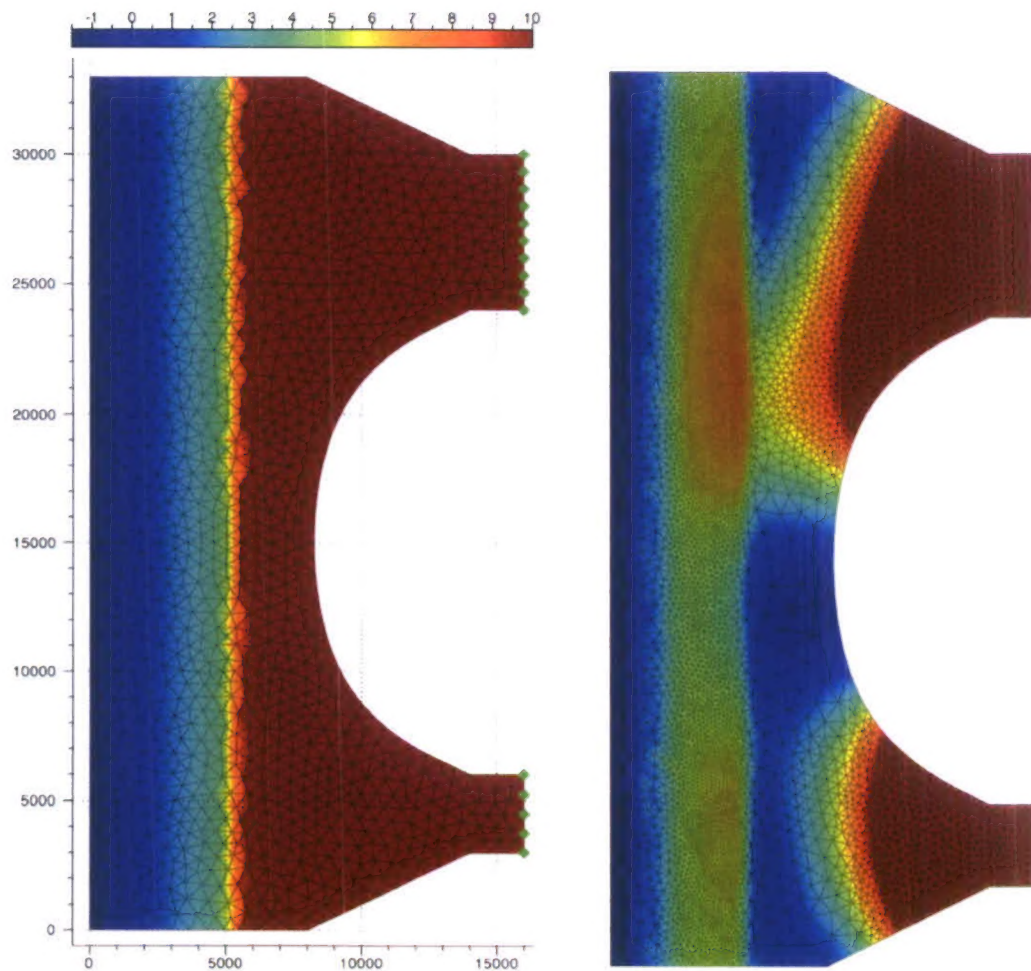
**Figure 4: (Left panels) Comparison of observed (red) and model-computed (black) vertically-averaged velocity components at the ADCP site. (Right) Major axis of vertically-averaged velocity at the ADCP site vs. mesh resolution.**

#### 4. Application of Open-Loop H-Adaption to Idealized Tidal Flats Domains

An idealized model of a tidal flat with two inlets (Figure 5, green diamonds) was constructed to evaluate the open loop h-adaption method. Along-flat currents are generated using tidal phase lag between inlets and asymmetric inlet widths. Both heuristic-based (using divergence of the bed stress) and Richardson's Extrapolation based methods were used to set the background lengthscale. In comparison with uniform refinement, local adaption driven by the flow solution produced meshes with lower discretization errors at a fixed computational cost. Convergence was found to be limited by interpolation errors between the coarse and fine meshes which confounds the accuracy of the error estimate. This method is currently being extended for use in realistic domains including Skagit Bay and the Massachusetts Coast.

#### 5. Evaluation of Wet/Dry Scheme in FVCOM

The ability of the flooding/drying scheme in FVCOM to resolve the propagation of the wet/dry interface and associated shear stresses was evaluated using comparison with laboratory experiments (Briggs et al, 1995) and comparison with a wet/dry interface resolving SWE (swe-hlle) solver on several classical test cases (e.g. Heniche et al., 2000). It was determined that the screen based scheme implemented in FVCOM can resolve the shear stress and propagation of the front during drainage if the dry threshold is sufficiently small (Figures 6,7).



**Figure 5: (Left) Initial Mesh and Bathymetry for the idealized two-inlet case. (Right) Mesh and divergence of bed stress after ten iterations of the open loop h-adaptive solver**

## RELATED PROJECTS

In this work we worked closely with other investigators participating in the ONR tidal flats DRI. The key collaborators included C. Sherwood and R. Signell (USGS, Woods Hole) who have assisted with the development, implementation, and validation of CSTMS within FVCOM as well as processing of bathymetry for the model domain. We also worked closely with D. Ralston (WHOI) and J. Lerczak (OSU) in the model development, validation, and application.

## DISSEMINATION

### Peer Reviewed Publications

Lerczak, J., D. Ralston, and G. Cowles, Annual and Inter-Annual Variations in the hydrodynamics of the Skagit River tidal flats: a numerical modeling study, submitted to Continental Shelf Research.

Cowles G. and A. Hakim, Application of Open Loop H-Adaptation to the Finite Volume Community Ocean Model, in preparation.

Cowles, G.W., A GPU-Accelerated Structured Adaptive Mesh Refinement Solver for Morphodynamic Studies of Sandy Tidal Flats, in preparation.

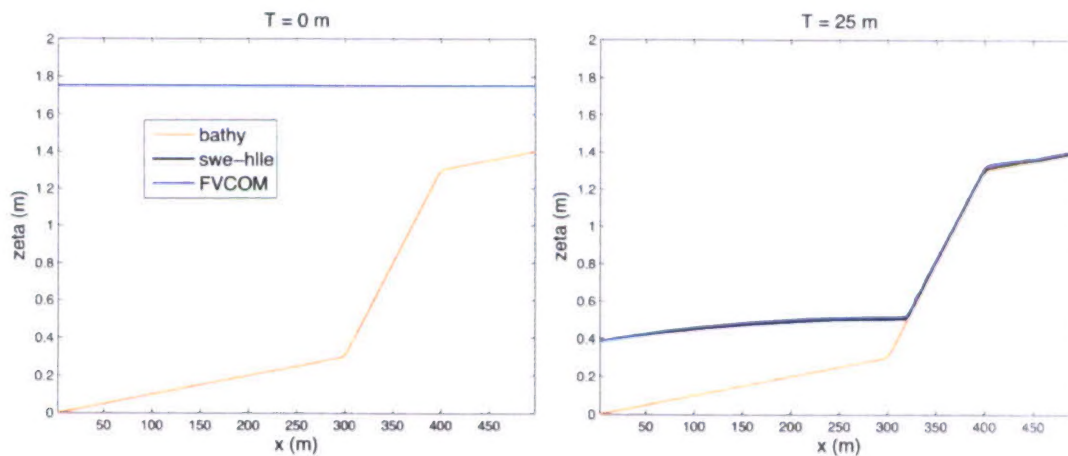
### Presentations

Cowles, G.W., E. Holmes, D.K. Ralston, and C. Sherwood, A wave-current-sediment model for Skagit Bay, AGU Fall Meeting, San Francisco, CA, 2010 (poster).

Cowles, G.W. and Y. Jung, An Adaptive Mesh Refinement Shallow Water Equation Solver for Validation of Wetting/Drying Processes on Tidal Flats, AGU Ocean Science Meeting, Portland, OR, February, 2010.

Cowles, G.W. and Y. Jung, Application of Open Loop H-Adaptation to an Unstructured Grid Circulation Model of the Skagit Delta, Coastal and Estuarine Research Federation, Portland, OR, November, 2009.

Cowles, G.W. Y. Jung, An FVCOM Model of Skagit Bay. ONR Tidal Flats Workshop, Boston, MA, October, 2009.



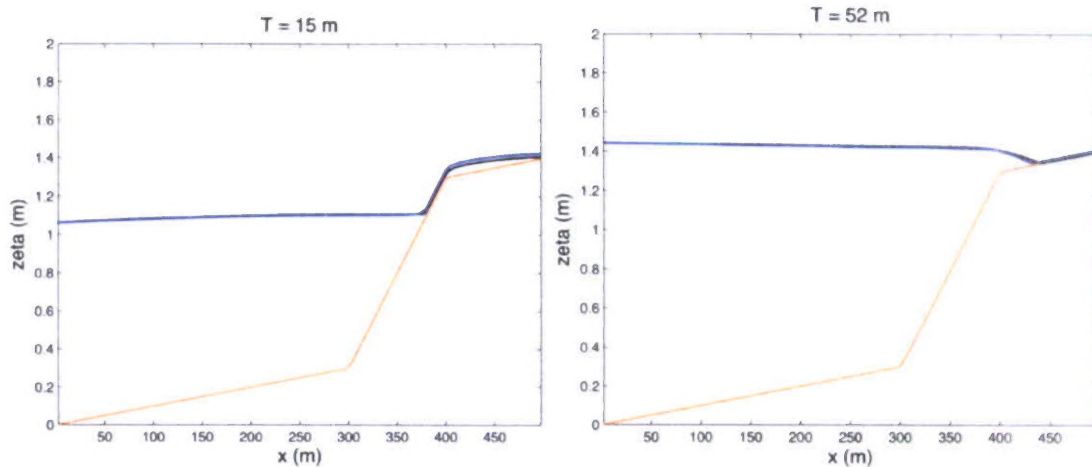


Figure 6: Comparison of model-computed free surface height using the FVCOM and the SWE-HLLE solvers for the *Heniche et al.* test case.

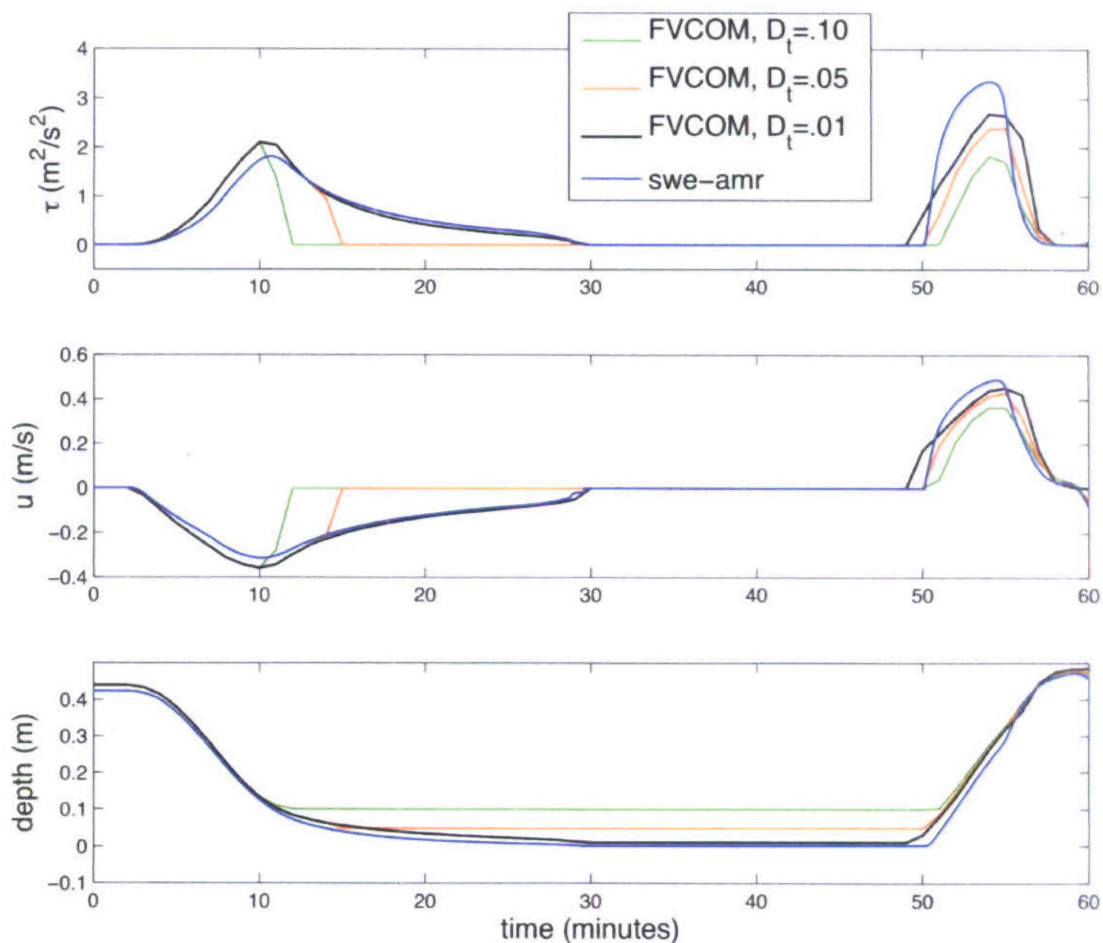


Figure 7: Time series of bed stress, vertically-averaged velocity, and depth at the mid-flat position in the *Heniche et al.* test case computed with SWE-HLLE and FVCOM using varying levels of the wet/dry threshold depth ( $D_t$ ).

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